ARIZONA DEPARTMENT OF TRANSPORTATION

REPORT NUMBER: FHWA-AZ87-826

LOOP DETECTOR SENSITIVITY VARIATION DUE TO BURIAL DEPTH

State of the Art

Final Report

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October 1987

Prepared for:
Arizona Department of Transportation
206 South 17th Avenue
Phoenix, Arizona 85007
in cooperation with
U.S. Department of Transportation
Federal Highway Administration

TECHNICAL REPORT DOCUMENTATION PAGE

1. REPORT NO.	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
FHWA-AZ87-826		

4. TITLE AND SUBTITLE
LOOP DETECTOR SENSITIVITY VARIATION DUE TO BURIAL DEPTH
State of the Art

5. REPORT DATE
October 1987

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
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8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Dr. Paul Russell
5902 East Caballo Lane
Scottsdale, AZ 85253

10. WORK UNIT NO.

11. CONTRACT OR GRANT NO.
HPR-PL-1(33) ITEM 826

12. SPONSORING AGENCY NAME AND ADDRESS
ARIZONA DEPARTMENT OF TRANSPORTATION
206 S. 17TH AVENUE
PHOENIX, ARIZONA 85007

13. TYPE OF REPORT & PERIOD COVERED
Final Report
June 1987-August 1987

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration

16. ABSTRACT

The characteristics and sensitivity of inductive loop detectors have been predicted for particular vehicle configurations and have been established empirically through years of experience. This report summarizes the information available and extends the sensitivity versus height calculations to include different models for vehicles of varying size. The degenerative effect on loop sensitivity of reinforcing steel in the roadway has been calculated.

In the absence of reinforcement, loop sensitivity is predicted to decrease at a rate of 4% for each additional inch separation between the loop and the average height of the vehicle. This decreased rate is independent of vehicle size.

Size and magnetic field distribution essentially determine loop application. Large loops exhibit reduced sensitivity to small vehicles. The magnetic field distributions for a small 6'x 6' quadrupole loop is stronger near its center. As a result it is more sensitive to small vehicles and provides better lane discrimination.

A major deficiency in loop theory is the lack of verification of results obtained from calculations. To verify theoretical models, a detailed experimental plan is presented.

The result of successful experimental verification will produce refined design criteria for determining presence, count and speed from inductive loop detector applications.

17. KEY WORDS
loop detectors
traffic control strategy
traffic surveillance

18. DISTRIBUTION STATEMENT
Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161

19. SECURITY CLASSIF. (of this report)	20. SECURITY CLASSIF. (of this page)	21. NO. OF PAGES	22. PRICE
Unclassified	Unclassified	32	

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Introduction

Inductive loops are the most versatile of the common traffic control devices. They are capable of obtaining traffic counts, indicating vehicle presence, measuring speed, noting loop occupancy and indicating queue length. Loops are excellent presence detectors. The size and shape of the detection zone is determined by the loop size, placement, separation and connection of loop combinations. They are relatively inexpensive and pose minimal problems after proper installation. The main disadvantages are cost in some cases and the inconvenience associated with installation in a completed roadway.

The basic operating principle of an inductive loop is that of interaction between the magnetic field produced by the loop and the conducting surfaces of the vehicle. The magnetic flux normal to a conducting surface induces eddy currents within that surface. These currents reflect an impedance back to the loop which usually results in a net decrease in system inductance. It is this decrease which is measured and defines the sensitivity of the loop.

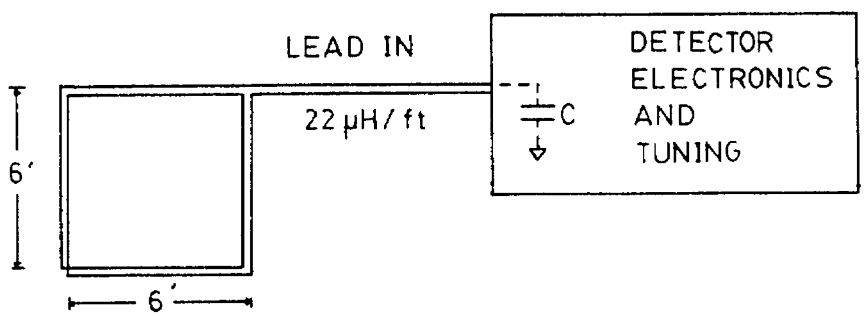


FIGURE 1. BASIC LOOP DETECTION SYSTEM

In a common system the loop and lead-in inductance, along with the detector electronic tuning capacitor, form a resonant circuit. With a frequency shift detector system the presence of a vehicle near the loop produces an increased frequency. Any increase above some predetermined shift will produce a call, if the shift and time duration are sufficient.

The detection of a vehicle will depend on the vehicle size and geometry relative to the strength and orientation of the magnetic field produced. The detection is strongly influenced by the distance from the loop conductors to the vehicle surface. Lead-in inductance will decrease the sensitivity of the loop detector, as also will the presence of other conducting materials.

Magnetic field distributions produced by the loops are distorted by the presence of conducting and magnetic material. Thus, loop detector performance will be effected when used on bridges or near concrete roadway reinforcing bars. These distortions, in addition to the wide variety of vehicles and positioning which must be accommodated, result in uncertain loop detection capability in marginal cases.

Detector systems should operate with a loop plus lead-in inductance of 50 to 700 μH at a frequency of 50 KHz. For proper operation system Q should be high, greater than 5, and the loop resistance to ground should be greater than 1 megohm.

The detector system should not respond to any vehicle which is further than 3 feet from the perimeter of the inductive loop.

Particular applications will require systems with different sensitivities.

These are classified as follows:

Class (1) - .13% (Δ1/1) or a 0.12 μH inductance change using 6'x 6'-3 turn loop with 100' of lead-in. This represents detection capability of a small motorcycle.

Class (2) - .32% (Δ1/1) or a 0.3 μH inductance change using a 6'x 6'- 3 turn loop with 100' lead-in.

Class (3) - 3.2% (Δ1/1) or a 3 μH inductance charge using a 6'x 6'- 3 turn loop with 100' of lead-in.

The maximum reduction in inductance for any test vehicle shall be 5.4% or 5uH using the loop configuration above.

Single loops should respond to vehicles with velocities from 5 to 80 mph. If the loops are used in a four circuit configuation the test speeds for response should be 5 to 20 mph.

Inductive Effects

The development given in Appendix A can be used to calculate the mutual inductance between two (2) current carrying loops, and, also the self inductance of a loop. Figure 2 illustrates the geometry for determining mutual inductance between loops, the loop detector and a second loop which is used to model a vehicle. Equation (A-3) is used in the calculation which involves mutual inductance between colinear conductors. Mutual inductance is negative for currents in opposite direction and positive in elements where currents are in the same direction. Segment 1-2 interacts with 5-6 (negative) and with 7-8, a smaller (positive) value, since the 7-8 is greater distance from 1-2.

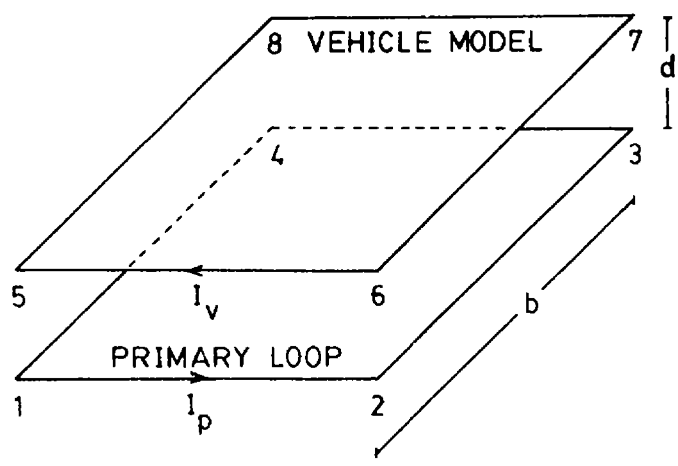


FIGURE 2. MODEL USED FOR CALCULATING LOOP SENSITIVITY.

The net result is a partial mutual inductance Mp given by

$$M_p = (-M_{1-2,\ 5-6} + M_{1-2,\ 7-8}) \qquad (1)$$

A similar calculation holds for 2-3 and segments 6-7 and 5-8. There is no interaction between orthogonal line segments. Considering all pairs of elements the mutual inductance between the two circuits is

$$M_t = 2(-M_{1-2,\ 5-6} + M_{1-2,\ 7-8} - M_{2-3,\ 6-7} + M_{2-3,5-8}) \qquad (2)$$

The self inductance of a rectangular loop is obtained by letting d of Figure (2) be the radius of the loop conductor.

As indicated by Eq (A-3) a small separation produces a strong interaction between elements. This basic principle illustrates the importance of positioning small vehicles near one of the loop conductors or varying the shape of the loop winding to assure that the small vehicle will be near a conductor.

Table 1 lists the calculated self inductance obtained for loops of various sizes and different numbers of turns. Commercial detectors will operate only over a limited range of acceptable inductance. Three turns of a small loop can usually be used and only one or two turns of the larger loops are allowable. In order to minimize the detrimental effects of the lead-in inductance, loop inductance should be maximized.

The range of allowable inductance, loop plus lead-in, will be specified by the particular detector.

TABLE 1 SELF INDUCTANCE FOR RECTANGULAR LOOPS (μH) CALCULATED VALUES

Loop Size (ft)	Turns 1	2	3	4	5	6	7
5 X 5	9	30	62	104	155	--	--
6 X 6	10	37	76	129	194	269	355
6 X 10	14	51	107	181	--	--	--
6 X 30	34	126	272	461	--	--	--
6 X 50	53	205	447	773	--	--	--
6 X 60	63	245	537	832	--	--	--
6 X 70	72	286	628	1092	--	--	--

In Table 1, spacing between loop conductors is 150 mils, center to center, wire size is #14 AWG.

The calculated values of mutual inductance vs separation between a single turn inductive loop, 6' X 6', and a single, shorted turn, representing the vehicle are shown in Table 2. It was assumed that the shorted turn was the same size as the primary loop and located directly above it. This represents an ideal situation. As can be noted from Table 2 the rate of change of mutual inductance decreases with increasing separation. As a result large vehicles of different effective heights above the surface would produce the same signal signature.

TABLE 2 MUTUAL INDUCTANCE BETWEEN A SINGLE TURN INDUCTIVE LOOP AND A 6'X 6' SINGLE SHORTED TURN (VEHICLE MODEL)

Loop Size	Vehicle height Above Loop (inches)	Mutual Inductance (μH)
6'x 6'	12	-1.73
	16	-1.39
	20	-1.14
	24	-0.96
	28	-0.81
	32	-0.69
	36	-0.59
	40	-0.51
	44	-0.44
	48	-0.38
	52	-0.34
	56	-0.30
	60	-0.28

The mutual inductance between a 6' X 6' primary loop and 4' X 4' and 2' X 2' vehicle shorted turn loop are given in Tables 3 and 4. The mutual inductance between colinear pairs was calculated using Eq (A-4). Equation (2) was then employed to determine the total inductance between the 2 loops.

Tables 2, 3 and 4 show the rapid decrease in interaction with decreasing area of the shorted turn. The tables also indicate that when the separation between loops is comparable to a side dimension the interaction is roughly constant for moderate changes in separation, but the interaction is weak.

TABLE 3 MUTUAL INDUCTANCE BETWEEN 6'X 6' PRIMARY LOOP AND CENTERED 4'X 4' PARALLEL SHORTED TURN (VEHICLE MODEL)

Vehicle Height Above Loop (inches)	Mutual Inductance (10^{-7} µH)
6	-10.07
8	- 9.49
10	- 8.87
12	- 8.26
18	- 6.49
30	- 4.00
36	- 3.13
42	- 2.52
48	- 2.04
54	- 1.64
60	- 1.32

TABLE 4 MUTUAL INDUCTANCE BETWEEN 6'X 6' PRIMARY LOOP AND A CENTERED 2'X 2' PARALLEL SHORTED TURN (VEHICLE MODEL)

Vehicle Height Above Loop (inches)	Mutual Inductance (10 µH)
6	-.781
8	-.777
10	-.772
14	-.760
18	-.745
24	-.719
36	-.656
42	-.622
48	-.591
54	-.560
60	-.530

Other Factors Affecting Loop Inductance

The equations used to determine inductance accounted for external flux linkages and did not include the effects of the flux within the conductors, Mills [b] has calculated the increases in inductance when the internal flux is considered. For a #14AWG loop operated at 20 kHz, the internal inductance was .014 µH/ft and at 100 kHz was .0075 µH/ft. For a 6' X 6' loop the external self inductance is

10.4 μH. Internal inductance would add .34 μH to this value. However, in assessing loop sensitivity it is the relative change in inductance rather than absolute value of change which is important. The change in absolute value is only about 3%. See Figure 3. This degree of precision exceeds that needed since modeling the vehicle as a shorted turn and locating it at some average height above the primary loop introduces large uncertainties into the problem.

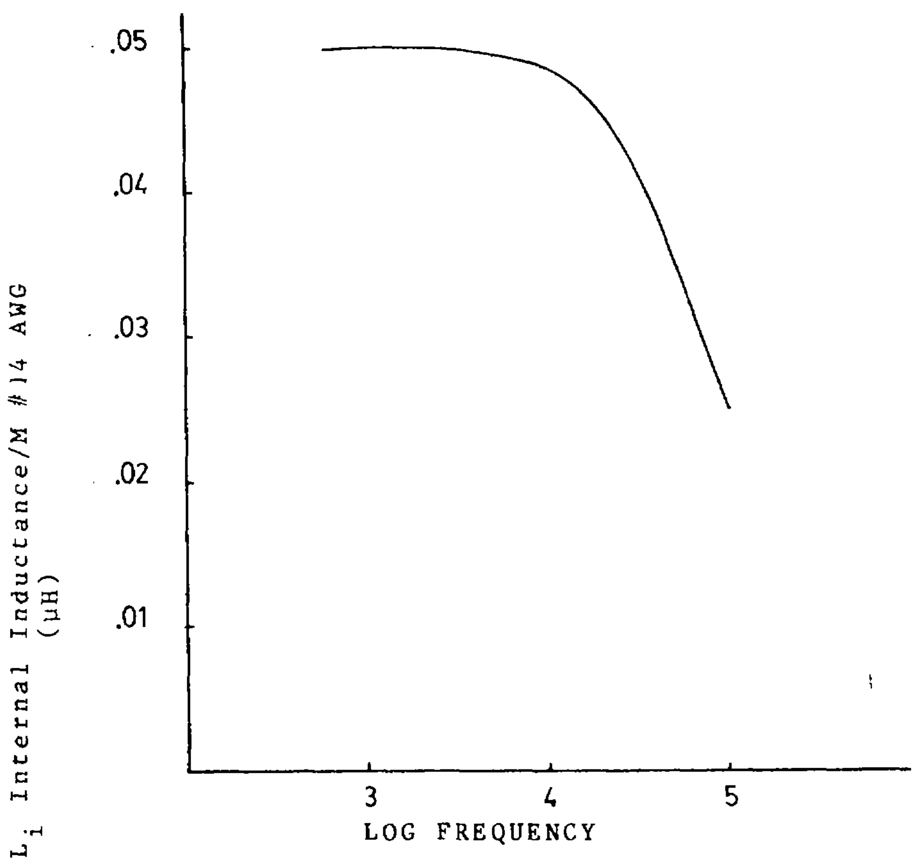


FIGURE 3. INTERNAL INDUCTANCE/M
OF THE LOOP WIRE

The steel surfaces of the vehicles have high permeability. This would tend to increase rather than decrease the inductance of a primary loop with a vehicle present. However, the effective magnetic path length in regions of high permeability is very short compared to the magnetic path length in air. As a consequence the increased permeability has negligible effect and can usually be ignored. Table 5 shows the approximate path lengths in regions of high permeability as a function of loop operating frequency.

TABLE 5 DEPTH OF MAGNETIC FIELD PENETRATION IN A CONDUCTING SURFACE

Operating Frequency (kHz)	Depth (mm)
20	0.79
30	0.64
40	0.56
50	0.50
60	0.46
70	0.42
80	0.40
90	0.37
100	0.35
110	0.34
120	0.32
130	0.31
140	0.30
150	0.29
160	0.28
170	0.27
180	0.265
190	0.258
200	0.251

Multiturn Inductive Loops

The inductance of a multiturn inductive loop can be determined from the self inductance values for each turn of the loop and the mutual inductance between the loops. Figure 4 illustrates the procedure. For a three turn loop this gives an equivalent inductance, L_e,

$$L_e = 3L_1 + 4M_{12} + 2M_{13}$$

where L_1 is the self inductance of a single loop, the

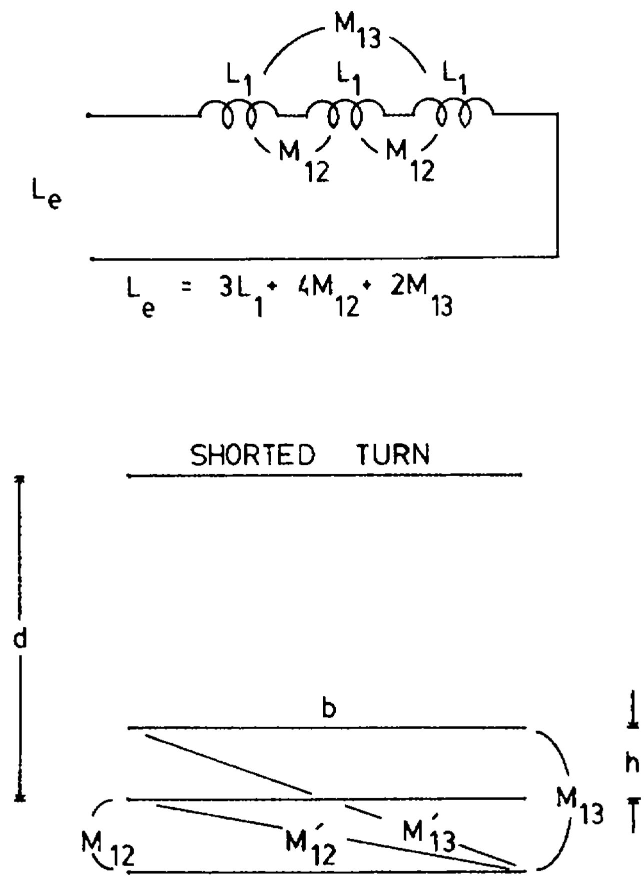


FIGURE 4. MODEL FOR DETERMINING THE EQUIVALENT INDUCTANCE OF A THREE TURN LOOP.

second term of the right hand side represents the mutual inductance between loops spaced h apart, and the last term is for mutual inductance at spacing 2h. When center to center spacing between loops conductors approaches the conductor diameter, the mutual inductance terms approach the value L_1 and $L_e = 9L_1$.

For the actual case L_e is always somewhat less than $9L_1$, (N^2 L, where N is a general number of turns). This is due to the leakage flux attributable to spacing between loops. The greater this spacing the smaller the self inductance. The spacing, h, is usually small compared to the vehicle separation "d" - As a consequence the mutual inductance between each loop turn and the vehicle shorted turn can be considered equal. The mutual inductance will increase by 3(N) but the self inductance will increase by less than $9(N^2)$.

As a result of the above the sensitivity of an N turn loop will be slightly greater than that of a single turn. Mills [c] has shown that the detection sensitivity increases somewhat with loop volume. That is the <u>maximum height above the loop at which a vehicle can be detected</u> is roughly proportional to the volume occupied by the loop conductors and for a given volume is independent of the number of loop turns.

Quadrupole Inductive Loops

Quadrupole loops are configured as two rectangular loops in series and positioned so that the currents in the center are parallel. Figure 5a illustrates. The two center conductors are laid in one slot. This configuration produces good lane discrimination compared to the rectangular loop, since the magnetic fields tend to be strongest near the center of the loop. In addition this configuration is sensitive to small vehicles and has been used to detect the presence of bicycles.

Detection of a vehicle can result from the interaction of the loop fields and either horizontal or vertical conducting surfaces. See Figure 5b. The calculated sensitivity will depend on the vehicle model chosen. In the case of the quadrupole, bicycle detection probably results from the loop's horizontal magnetic field producing eddy currents in vertical surfaces of the bike.

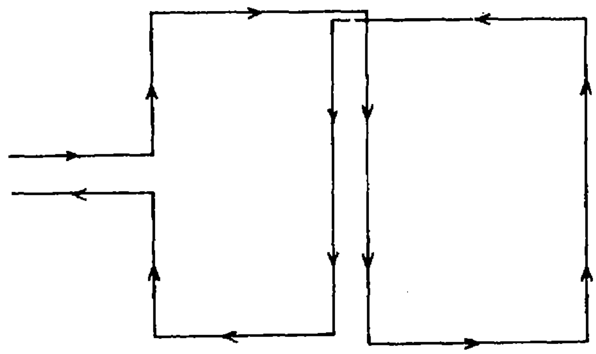


FIGURE 5A QUADRUPOLE LOOP.

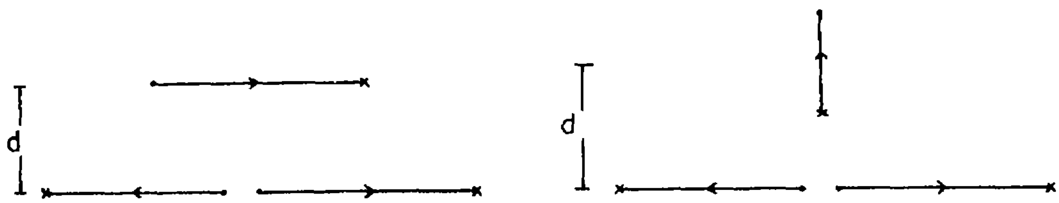


FIGURE 5B QUADRUPOLE LOOP DETECTOR

In detecting vehicles with any given loop configuration the location of the vehicle relative to the loop conductors, and its height relative to the loop, are critical elements in establishing detectability.

Calculated and measured inductance values for the quadrupole loop compared well [d]. Calculated values can be obtained from the summation of mutual inductances as done in the case of rectangular loops and using this approach the self inductance value for a single turn 6'x 6' quadrupole (two 6'x 3' loops in series designated L^{121}) was 17.8μH. This compared well with calculations by others which gave 17.26μH and 18μH at 47kHz. Adequate models exist for the calculation of self inductance.

Other Loop Configurations

Diamond loops, double rectangular, compound loops (large outside loop about a smaller inner loop in series), hexagonal loops and double triangular loops have been investigated to determine the magnetic field distribution and hence the maximum height at which a given vehicle might be detected. Laboratory studies [e] have determined the cross-lane along lane and vertical magnetic field components.

As expected each configuration will have particular advantages for detecting a type or size of vehicle. The selection process is then a compromise based on expected conditions. Davies'[e] work seems to indicate a trend in magnetic field characteristics associated with the loop configurations analyzed. That is, compound loops such as hexagonal, triangle, quadrupole have better area coverage than the rectangular loop. The field distribution is somewhat more uniform horizontally. The price paid is that the vertical coverage is not as good as for the rectangular loop. In a crude sense for a given size loop the distribution of the flux which determines mutual inductance can be altered but the total flux is roughly constant.

Approximate Loop Inductance Formulas

Simplified expressions can be used to determine the self inductance of rectangular and quadrupole loops. Several are noted below. While these expressions are useful to assure that the loop inductance is compatible with the detector electronics, they do not give any indication of system sensitivity. The latter depends on the both mutual and self inductances. For a single turn loop [f]

$$L = .5P \ (\mu H)$$

where P is the loop perimeter (ft).

The inductance for a single turn loop of #14 AWG is

$$L = .45P \ (\mu H).$$

The coefficient will vary with conductor size for the multiturn loop [f]

$$L = .46 \ PN \ (\mu H)$$

where N is the number of loop turns.

Self inductance of quadrupole loops can be approximated by [d]

Single Turn $L^{121}(\mu H) = .6402\ A(ft) + 2.3069\ B(ft)$

Two turn $L^{242}(\mu H) = 2.0619\ A(ft) + 8.1618\ B(ft)$

Three turn $L^{363}(\mu H) = 4.0665\ A(ft) + 17.1167\ B(ft)$

where A and B are the element lengths in feet of the qudrupole.

Detection Sensitivity of Rectangular Loops

The previous sections concerned the calculations of self and mutual inductance for rectangular loops. These parameters are essential to determine the detector sensitivity of an inductive loop. The latter is the **subject of this section. Figure 6 illustrates the basic detection configuration.**

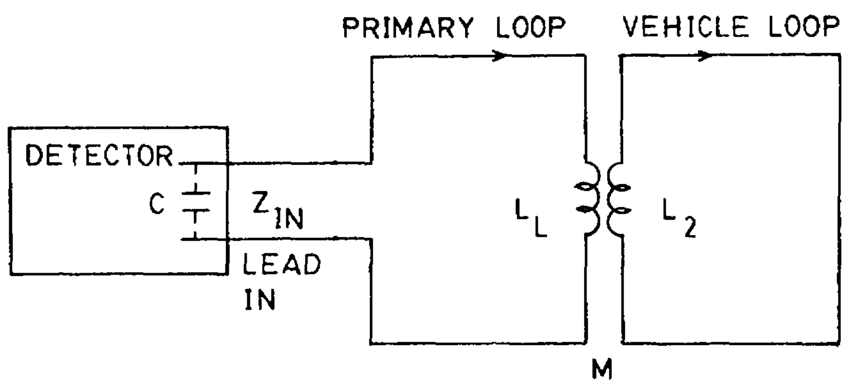


FIGURE 6. COUPLING BETWEEN INDUCTIVE LOOP AND VEHICLE.

Electronics associated with the loops can be set to register a call when some threshold value of inductance change is exceeded. An example would be the percent inductance change seen at the input terminals of the electronics. As the lead-in connecting the loop to the electronics has appreciable inductance, .22 μH/ft, it has an adverse effect on system performance. The presence of reinforcing steel in the pavement will also alter detection performance.

Mills [g] has calculated the effects of reinforcing mesh on loop sensitivity. The closer the reinforcing mesh is to the loop, the worse is the sensitivity. To a modest extent the sensitivity loss is also related to the vehicle height above the loop. The reinforcing bar has less effect in sensing high vehicles than those vehicles with low profiles.

Most of the newer digital vehicle detectors measure essentially a change in frequency. This is processed either as a frequency change or as a change in loop signal period.

The loops are generally operated in high Q resonant circuits which give a frequency dependence

$$f_D = \frac{1}{2\pi C L_D}$$

where f_D is the loop oscillator frequency, L_D is the loop plus lead-in inductance at the detector terminals, and C is the capacitance at the detector terminals plus the internal tuning capacitance. The normalized changes in frequency, $\Delta f/f_D$ is related to inductance change by

$$\frac{\Delta f_D}{f_D} = -\frac{1}{2} \frac{\Delta L_D}{L_D} = \frac{1}{2} S_D$$

where S_D is the detector sensitivity. If the lead-in inductance is negligible the loop sensitivity, S_L , is

$$S_L = \frac{\Delta L_L}{L_L}$$

The relative change in loop inductance is of prime importance in vehicle detection.

Changes in loop inductance can be estimated by considering the vehicle effect modeled by a transformer (loop) coupled to a shorted turn (vehicle). Figure 6 is an idealized version of this model. The resultant loop sensitivity is

$$S_L = -M^2 / L_L L_2$$

where M is the mutual inductance between the inductive loop and the vehicle modeled as a shorted turn and L_2 is the equivalent self inductance of the vehicle. Variability and uncertainty in values for the latter two parameters points to the problem in predicting system performance even under idealized conditions.

Sensitivity Calculations

Estimates of loop sensitivity for the idealized case are of value in establishing trends and providing guidelines for modifying loop configurations and for designing experiments to establish system performance or to validate vehicle models.

The data of Tables 2, 3 and 4 which give mutual inductance between the 6'x 6' single primary loop and shorted turn of different dimensions were used to obtain percent loop sensitivity, S_L , as a function of vehicle height. See Figure 7. The upper curve of the figure gives the sensitivity for a 6'x 6' 3 turn inductive loop interacting with a centered 6'x 6' shorted turn [g]. The single turn inductive loop is slightly less sensitive to the 6'x 6' shorted turn. Decreasing the size of the vehicle surfaces results in the sensitivities shown by the two bottom curves. These data were obtained for vehicles modeled as centered horizontal surfaces. Any displacement from center would have considerable effect on the result. In some cases a vertical conducting plane may represent a more appropriate surface for determining sensitivity.

Regardless of the assumed sizes of the shorted turn, all appear to change sensitivity at the same rate, - 4% per inch of increased separation between the loop and vehicle model.

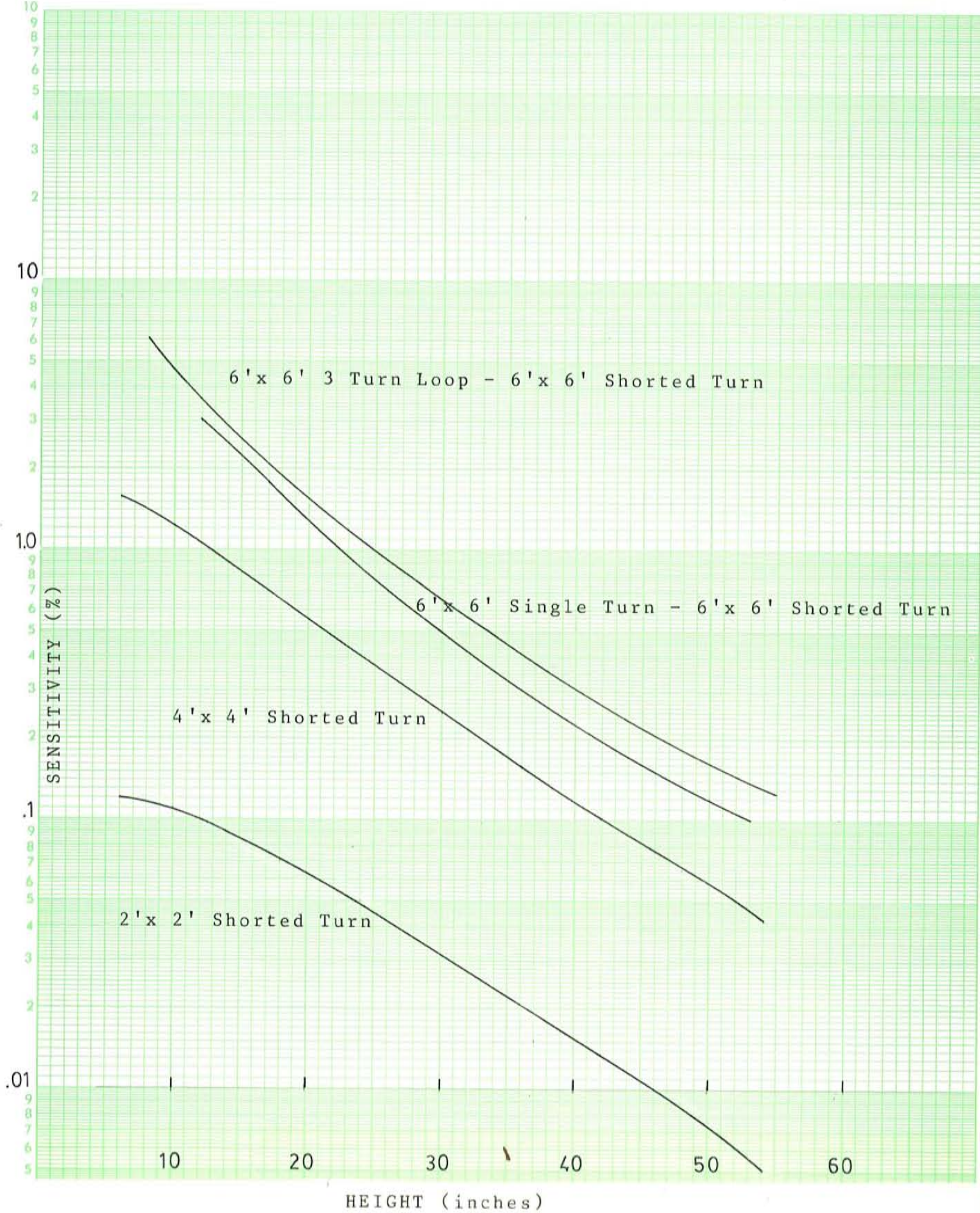


FIGURE 7. LOOP SENSITIVITY VARIATIONS RELATED TO VARIOUS-SIZED VEHICLES.

To check the results of the calculations, the sensitivity determination for 6'x 6' single turn inductive loop was modified and compared with Mills' results for a 3 turn loop. The modification consisted simply of substituting the inductance of the three turn loop for that of a single turn loop and using the mutual inductances given in Table 2. Figure 8 shows good comparison.

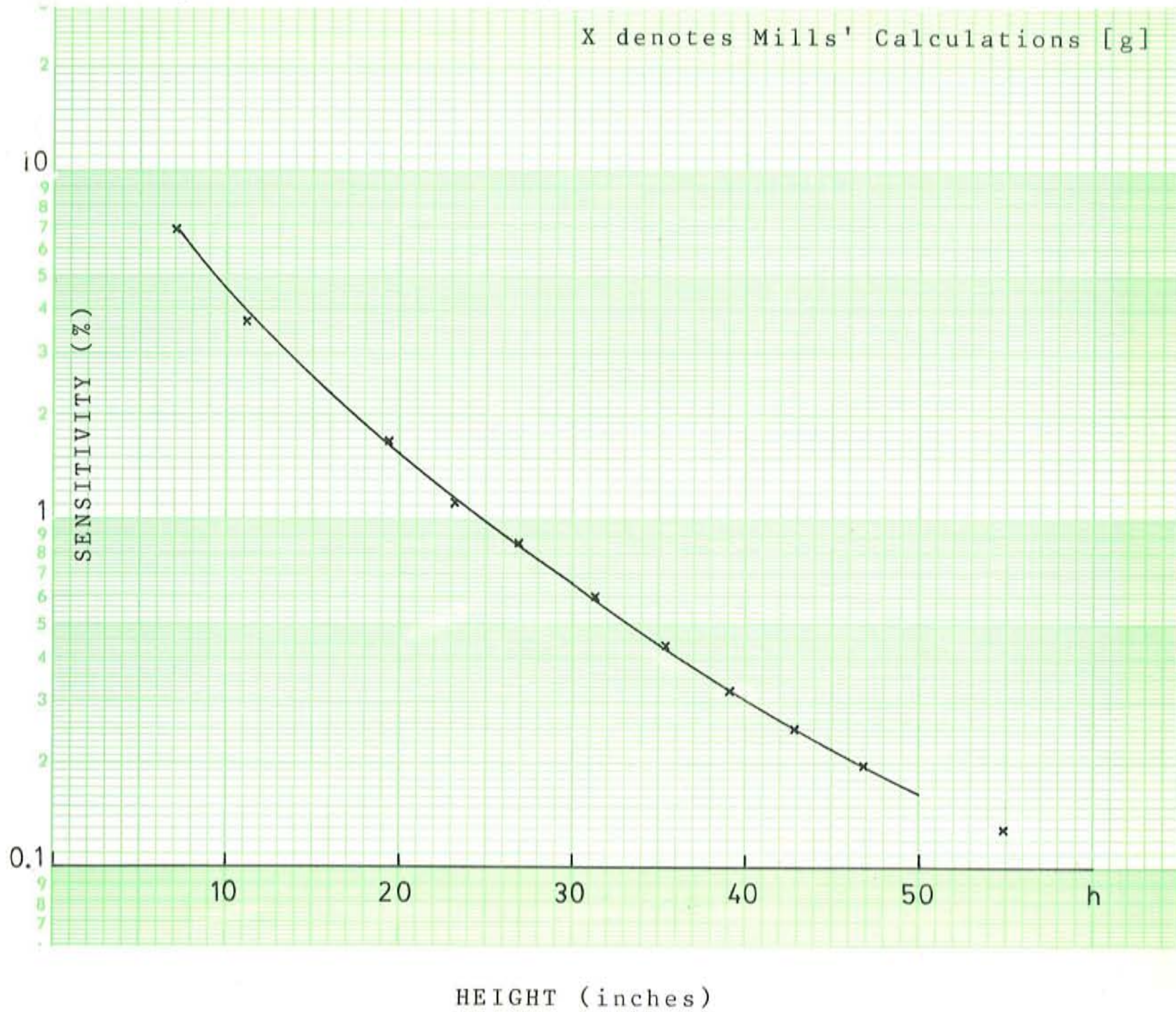


FIGURE 8. SENSITIVITY RESULTS OBTAINED FROM TWO DIFFERENT MODELS.

Quadrupole loop sensitivity can be calculated using the procedure cited above. Estimates of the mutual inductance between the quadrupole loop and shorted turns of different sizes and orientations were made. This information was used to estimate sensitivity of a single turn quadrupole loop, 6'x 6' configured L[121]. See Table 6.

TABLE 6 CALCULATED SENSITIVITY OF A QUADRUPOLE LOOP

Shorted Turn	Orientation	Height	Sensitivity
6'x 6'	Horizontal	12"	1.5%
6'x 4'	Horizontal	12"	.96%
6'x 2'	Horizontal	12"	.19%

If the vehicle is modeled as a 6'x 1' vertical shorted turn, 6" above the center conductors, the sensitivity is 2.5%. This compares with a horizontal 6' x 1' shorted turn sensitivity, at the same height, of about .5%.

Accuracy of Speed Measurements

Speed measurements depend on sensing the passage of a vehicle over two separated loops and noting the time difference in the responses obtained at the two loop detection units.

The measurement usually involves calculating the ratio of the distance to time between two, generally 6'x 6' loops. Satisfactory loop response is obtained if a detector output pulse is obtained with a delay between 75 to 150 millisecs. This can lead to considerable error in speed measurement as

$$\Delta V = \frac{d}{t} \Delta t$$

where Δt is the uncertainly in time due to finite response time of the loops. With d, the spacing between the leading edges of two loops taken as 100' the fractional error can be written as

$$\Delta V = \frac{V \Delta t}{t} \qquad \text{or} \qquad \frac{\Delta V}{V} = \frac{V \Delta t}{d}$$

For V = 60 mph and a time uncertainty of .1 second the fractional error would be

$$\frac{\Delta V}{V} = .09$$

This error can be reduced by selecting systems which have the same response time or by providing processing electronics to shape the individual pulse outputs and trigger the counter circuitry on the same portion of each output pulse.

Speed measurement errors could be effectively reduced by shortening the response time, decreasing the threshold levels of the loop detectors, or through some processing techniques which would compensate for known delay differences.

Exerimental Results

Some comparisons have been made between predicted and observed sensitivities obtained from inductive loops. However, these observations are scarce and they were not carried out in a systematic program. In essence the comparisons provide spot checks which yield reasonably good results.

Mills [g] cited the sensitivity observed when a Mercury station wagon interacted with an inductive loop detector. The average height of the wagon was taken as 6" and it was centered over a 6'x 6' inductive loop. Representing the vehicle by a shorted turn predicted a sensitivity change of 6%. The observed change was within 3% of the predicted value. A similar accuracy was obtained when a Ford Falcon was used as the test vehicle. However, changes in loop sensitivity as a function of relative vehicle position, the type of vehicle and its effective height above the loop have not been determined in a systematic program.

Recommendation for Further Study

The paucity of experimental results relating vehicle size and type and to detection sensitivity, is a major problem in the design of installations. If reasonable guidelines are established the basic design could be initiated by using a particular size shorted turn as a reference.

There are three major areas which require experimental work.

1) The model developed for the vehicle, the shorted turn, requires verification to determine accuracy and applicability.

2) The effects of subsurface reinforcing bar will adversely effect the detectibility of vehicles. The closer the reinforcing bar to the inductive loop the more adverse the effect. The reinforcing bar, like the vehicle, will be subject to eddy currents induced by the loop's magnetic field. However, eddy currents in the rebar and the adverse effects on sensitivity can be reduced. This could be accomplished by minimizing the electric current in the rebar. This is done by having an insulated coating on the bar or by not having any cross members in electrical contact. The effectiveness of these measures has not been investigated.

3) The use of inductive loops on bridges or structures containing large amounts of steel presents particular problems. This environment disturbs the expected magnetic field distribution. The change depends on the immediate structure. California [h] prefers the use of magnetic sensors on bridges rather than inductive loops. However Illinois [i] has used a technique where the inductive loop is imbedded in a channel. This tends to control the field distribution over the loop area and has allowed use on bridges. The latter should be investigated by measuring the field distribution from channeled and unchanneled loop installations.

The first two items above could be investigated in a rather systematic manner to (a) develop some guides for vehicle type versus detection sensitivity and (b) determine the effects of reinforcing steel and develop techniques to minimize the adverse effects. The procedure recommended would be:

1) Verify the shorted turn model for the vehicle.

This could be done by using conducting plates of various sizes with holes in the center to simulate the vehicles. The test would consist of using a commercially available detection system and observing the sensitivity changes when the position, orientation and height of the conducting plate are varied. These measured values would be compared with the predicted sensitivity for the particular geometry considered. This process would, if successful, verify the shorted turn model.

Sensitivity - size - orientation graphs could then be prepared. Further validation would involve relating the sensitivity obtained from a vehicle and correlating it with a location on the graph. This would establish correspondence between the vehicle and its shorted turn representation.

2) Evaluate the effects of reinforcing rod in concrete pavement.

The tests of item (1) would be repeated in the presence of rebar. Additionally, different configurations of reinforcing rod would be tested to determine the net effect on detection. Tests of interest would involve:

a) Insulating crossed rods to prevent electrical contact.
b) Varying the separation between the rebar and the inductive loop.
c) Determining the effects on detection sensitivity of different rebar geometries, that is dowels, longitudinal bars only and other possible electrically insulted configurations.

3) Evaluate the performance characteristics of quadrupole loops.

Quadrupole loops offer better lane discrimination, are reportedly able to detect smaller vehicles than rectangular loops offer better lane discrimination, and are reportedly able to detect smaller vehicles than rectangular loop inductors. However, this may depend on the location of the vehicle within the loop and its size, orientation and height. The tests described in shorted turn verification would be conducted using quadrupole loops.

In summary the studies which should be performed for rectangular and quadrupole loops are:

a) Verification of the shorted turn model for the vehicle.
b) Establishment of the correspondence between the sensitivity change produced by the size and height of a shorted turn and by a particular vehicle.
c) Determination of the effects of reinforcing bar on the detector sensitivity.

Experimentation to verify models and obtain the required data would be highly labor intensive, but the level of work could be carried out by technical assistants. Minimum engineering supervision and time would be required. It is assumed that detector systems, inductive loops and an experimental site would be provided by ADOT. A cost estimate is outlined.

Period - 2 years (items below are per year)

2 Full Time Technical Assistants	$ 20,000
2 Months Senior Engineer	14,000
1 Secretary (4 months)	5,000
Communications	300
Travel	1,000
Equipment	4,000
TOTAL	$ 44,300

With the exception of the inductive loops and the loop detector system, most of the equipment required is commonly used in electronics laboratories and would be readily available.

The following outlines the project recommended.

MODEL VERIFICATION

6'x 6' Primary Loop	Shorted Turn Size	Sensitivity at 6 inches Horiz	Sensitivity at 6 inches Vert	Sensitivity at 12 inches Horiz	Sensitivity at 12 inches Vert
No Rebar	6'x 6'				
	6'x 4'				
	4'x 4'				
	4'x 2'				
	2'x 2'				

6'x 6' Quadrapole Loop	Shorted Turn Size	Sensitivity at 6 inches Horiz	Sensitivity at 6 inches Vert	Sensitivity at 12 inches Horiz	Sensitivity at 12 inches Vert
No Rebar	6'x 6'				
	6'x 4'				
	4'x 4'				
	4'x 2'				
	2'x 2'				

Do selective measurements as above with rebar at 3 different levels below the primary loop.

Do selective measurements with the quadrupole in the presence of rebar.

Field test vehicle sensitivity.

Vary the position of the shorted turn relative to the primary loop for several selected loop to shorted turn separations.

Test Procedures for Inductive Loops

Inductive loop detectors usually fail because of:

(a) Detection unit failure
(b) Utility construction
(c) Poor sealants allowing moisture entry
(d) Cracking and movement of pavement
(e) Poor splicing or faulty electrical connectors
(f) Lightning surges.

False calls can be generated by:

(a) Crosstalk - caused by inductive or capacitive coupling between loops or lead-in wire,
(b) False detection due to vehicles outside the designated signal zone. This is usually caused be excessive levels of sensitivity on long loops.

The cause of failure, in some cases, can be determined by visual inspection. However, proper operation of the detection system requires a high Q circuit. This implies that the series resistance in the loop plus lead-in wire be below a specified value, and that the shunt resistance to ground be very high. A megger would be used to check the resistance to ground. This checks not only the latter parameter but also insulation breakdown at high voltage.

The Q of the circuit can be determined from the frequency response curve of the loop plus lead-in wire. This would involve replacing the detector unit with a variable frequency oscillator which operates over the detection range. An ac voltmeter is used to measure the response. The resonant frequency, f_r, is determined when the maximum voltage, V_m, is measured. The bandwidth is determined from the frequency spread about f_r, where the response lowers to $.7V_m$. The Q is then determined from the ratio of resonant frequency to frequency spread.
To check sensitivity of the loop detection system a sensitivity standard or "a standard" vehicle should be positioned above the loop. This changes the oscillator to the new resonant frequency, f_2, and will provide data which allows percent sensitivity, S, to be determined.

Testing of inductive loop systems requires the following equipment:

(a) Ohmmeter
(b) AC voltmeter (high impedance input), millivolt ranges
(c) Frequency counter
(d) Variable frequency oscillator 20 KHz to 200 KHz
(e) Megger

References

[a] Traffic Data Handbook, FWHA -IP-85-1, Available from NITS, Springfield, VA. 22161

[b] Mills, Milton K., Self Inductance Formulas for Multi-Turn Rectangular Loops Used with Vehicle Detectors, U.S. DOT Federal Highway Administration

[c] Mills, Milton K., Vehicle Detector Sensitivity Formulas for Multi-Turn Rectangular Loops U.S. Department of Transportation, Federal Highway Administration, Washington, DC

[d] Mills, Milton K., Self Inductance Formulas for Quadrapole Loops used with Vehicle Detectors. U.S. Department of Transportation Federal Highway Administration, Washington DC.

[e] Davies, P., Salter, D.R., and Bettison, M., Loop Sensors for Vehicle Classification, Dept. of Civil Engineering, University of Nottingham.

[f] Link, Advanced Products Division, Link Inductance Loop Analysis Project, Final Report P. 67, August 1968.

[g] Mills, Milton K. Inductive Loop Detector Analysis. U.S. Department of Transportation, Federal Highway Administration, Washington, DC.

Appendix

Calculation of Mutual or Self Inductance

The self or mutual inductance associated with large rectangular loops where the current is carried by small diameter conducting wires is of primary interest. The main or exciting loop clearly matches this description. Experience has shown that reasonable detector performance can be predicted by modeling the vehicles or roadbed reenforcing steel by large single turn shorted loops. This section develops formulas which estimate inductance values for the loops and between separated loops. These values in turn are used to estimate the detection sensitivity of the rectangular loop.

Inductance can be determined from the magnetic flux linkages produced by circuit #1 which link circuit #2. Dividing this quantity by the current #1 yields the mutual inductance. The self inductance of a single loop is **determined by calculating the mutual inductance when the separation between the loops is taken as the radius of the conductor.**

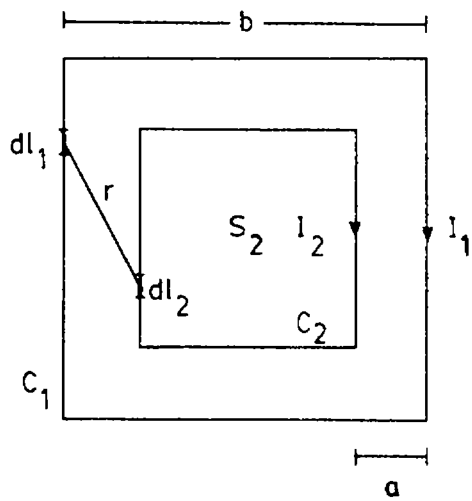


FIGURE A-1

The flux, ϕ, linking circuit C_2 is calculated from

$$\phi = \int_2 \bar{B}_1 \cdot \overline{ds}_2 \, .$$

where $\bar{B}_1$ is the flux density generated by circuit 1 and ds_2 is an elemental area enclosed by C_2. The above form is not convenient for the calculations required. A more convenient form is obtained by using the magnetic vector potential, A, which is related to $\bar{B}$ by $B = \mathrm{Curl}(\bar{A})$. This yields

$$\phi = \oint_{C_2} \bar{A} \cdot \overline{dl}_2$$

where the integration is over the conductor perimeter C_2 surrounding the area S_2. The vector potential is related to the current in C, by

$$\bar{A} = \frac{\mu \cdot I_1}{4\pi} \oint_{C_1} \frac{\overline{dl}_1}{r} \, .$$

The flux linkages can then be expressed as

$$\phi = \frac{\mu_0 I_1}{4\pi} \oint_{C_1} \oint_{C_2} \frac{\overline{dl}_1 \cdot \overline{dl}_2}{r}$$

and the mutual inductance by

$$M = \frac{\mu_0}{4\pi} \oint_{C_1} \oint_{C_2} \frac{\overline{dl}_1 \cdot \overline{dl}_2}{r} \, .$$

Inductance between two Conductors

The formula developed above can be used to determine the inductance between two current carrying conductors, length b, separated by a distance, d.

$$M = \frac{\mu_0}{4\pi} \int_1 \int_2 \frac{dx^1 \, dx}{[d^2 + (x-x^1)^2]^{\frac{1}{2}}}$$

This can be rewritten as

$$M = \frac{\mu_0}{4\pi} \int_1 dx^1 \int_{-x^1}^{b-x^1} \frac{d(x-x^1)}{[d + (x-x^1)^2]^{\frac{1}{2}}}$$

Integration and substitution of the limits yields

$$M = \frac{\mu_0}{4\pi} \int_0^b dx^1 \quad \{\ln(b-x^1) + \sqrt{(b-x^1)^2 + d^2} \\ -\ln(-x^1 + \sqrt{x^{1\,2} + d^2}\}$$

The evaluation of M can be completed by noting that

$$\int \ln\,[f(x^1)] \quad dx^1 = x^1 \ln\, f(x^1) - \int x^1/f(x^1)\, \frac{df(x^1)}{dx^1}\, dx^1$$

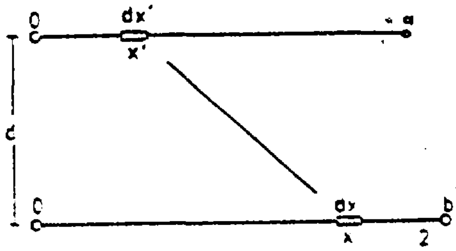
applying the above to Equation (A-1) yields

$$M = \frac{2\mu_0}{4\pi}\{\, b\ln\left[\frac{b+\sqrt{b^2+d^2}}{-b+\sqrt{b^2+d^2}}\right]^{\frac{1}{2}} + d - \sqrt{b^2+d^2}\,\} \qquad (A-2)$$

When the separation $d \ll b$, M reduces to

$$M = \frac{\mu_0 b}{2\pi} \quad \{\ln(\frac{2b}{d}) - 1\} \qquad (A-3)$$

This form clearly shows the dominant role that the separation between loops has in the final result.
When the two conducting filaments are different lenghts as illustrated in Figure (A-2)



The inductance can be estimated by following the procedure previously described. The result is

$$M = \frac{\mu_0}{4\pi}\,\{\ln[(b-a) + \sqrt{(b-a)^2 + d^2}\,]^{a-b} + \ln\frac{[b+\sqrt{b^2+d^2}\,]^b}{[-a+\sqrt{a^2+d^2}\,]^a} \\ + \sqrt{(b-a)^2+d^2} - \sqrt{b^2+d^2} - \sqrt{a^2+d^2} + d\} \qquad (A-4)$$

Equations (A-2) - (A-4) can be used to estimate mutual and self inductance when the approriate values are selected for a, b, and d.